Gravitational Waves From Neutron & Strange Quark Stars

Supported by the National Science Foundation
http://www.ligo.caltech.edu

Gregory Mendell LIGO Hanford Observatory

LIGO-G040443-00-W

The Neutron Star Idea

- Chandrasekhar 1931: white dwarf stars will collapse if M > 1.4 solar masses. Then what?
- Chadwick 1932: discovers the neutron.
- Landau 1932: suggests stars have neutron cores.
- Oppenheimer & Volkoff 1939: work out NS models.
- Baade & Zwicky 1934: suggest SN form NS.

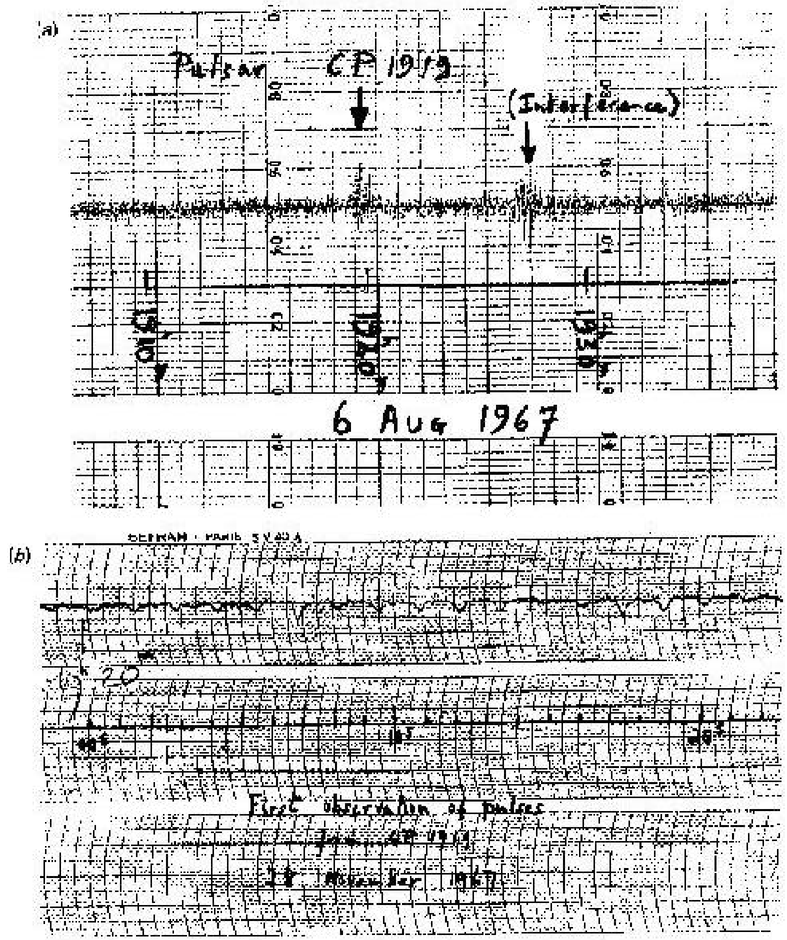
(http://www.jb.man.ac.uk/~pulsar/tutorial/tut/tut.html; Jodrell Bank Tutorial)

SN 1987A

http://www.aao.gov.au/images/captions/aat050.html

Anglo-Australian Observatory, photograph by David Malin.

Discovery of Pulsars



- Bell notes “scruff” on chart in 1967.
- Close up reveals the first pulsar (pulsating radio source) with P = 1.337 s.
- Rises & sets with the stars: source is extraterrestrial.
- LGM? 
- More pulsars discovered indicating pulsars are natural phenomena.
- Hewish, wins 1974 Nobel Prize.

Figure 2: Discovery observations of the first pulsar. (a) The first recording of PSR 1919+21; the signal resembled the radio interference also seen on this chart. (b) Fast chart recording showing individual pulses as downward deflections of the trace. From Lyne & Graham-Smith 1990 [23].

www.jb.man.ac.uk/~pulsar/tutorial/tut/node3.html#SECTION00012000000000000000

A. G. Lyne and F. G. Smith. Pulsar Astronomy. Cambridge University Press, 1990.

Pulsars = Neutron Stars

•From the Sung-shih

(Chinese Astronomical Treatise): "On the 1st year of the Chi-ho reign period, 5th month, chi-chou (day) [1054 AD], a guest star appeared…south-east of Tian-kuan [Aldebaran].(http://super.colorado.edu/~astr1020/sung.html)

•Pacini 1967: neutron stars power the crab nebula

• Gold 1968: pulsars are rotating neutron stars.

- ~~orbital motion~~
- ~~oscillation~~
- rotation

http://antwrp.gsfc.nasa.gov/apod/ap991122.html

Crab Nebula: FORS Team, 8.2-meter VLT, ESO

Pulsars Seen and Heard

Play Me

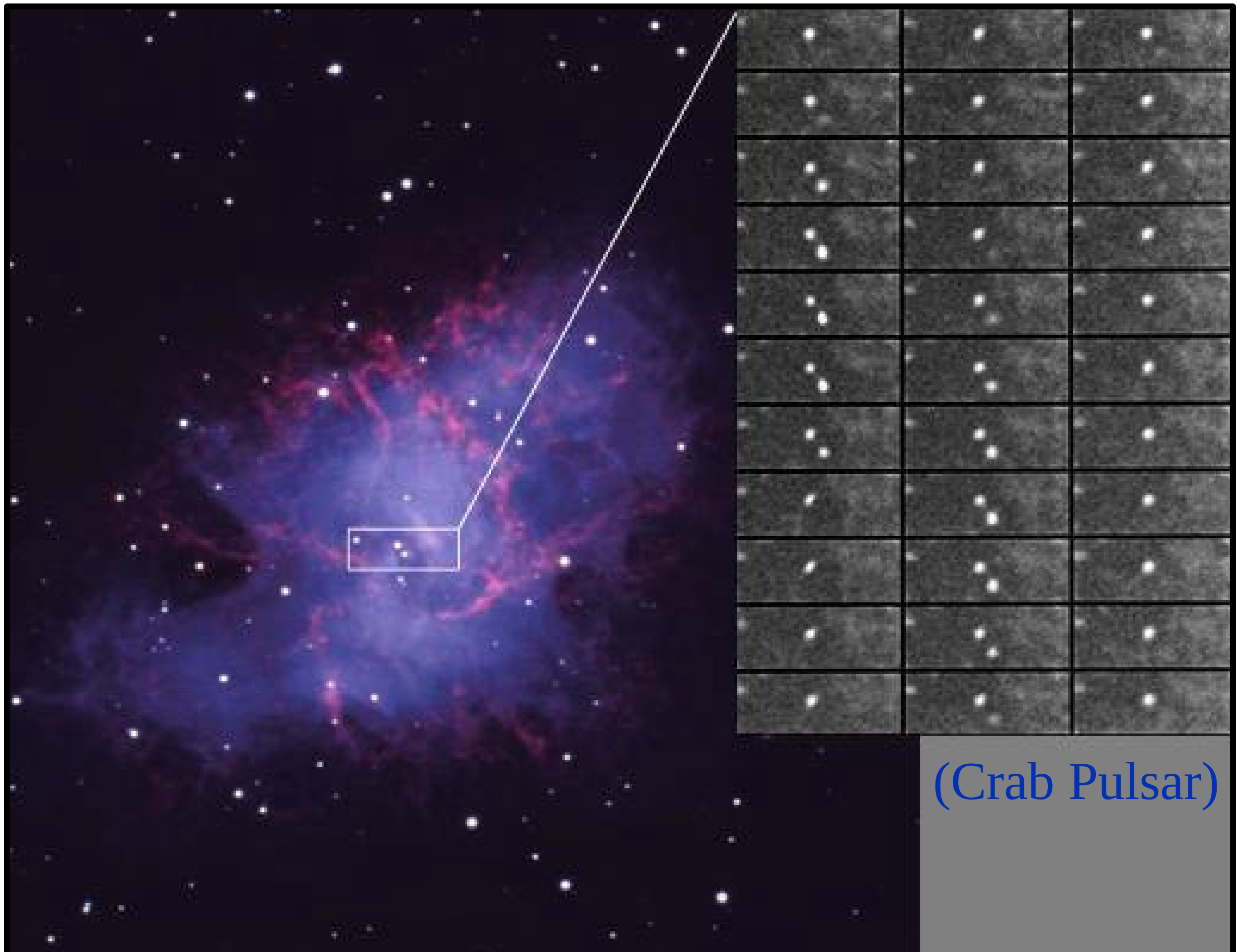
(Vela Pulsar)

http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html

Jodrell Bank Observatory,

Dept. of Physics & Astronomy,

The University of Manchester



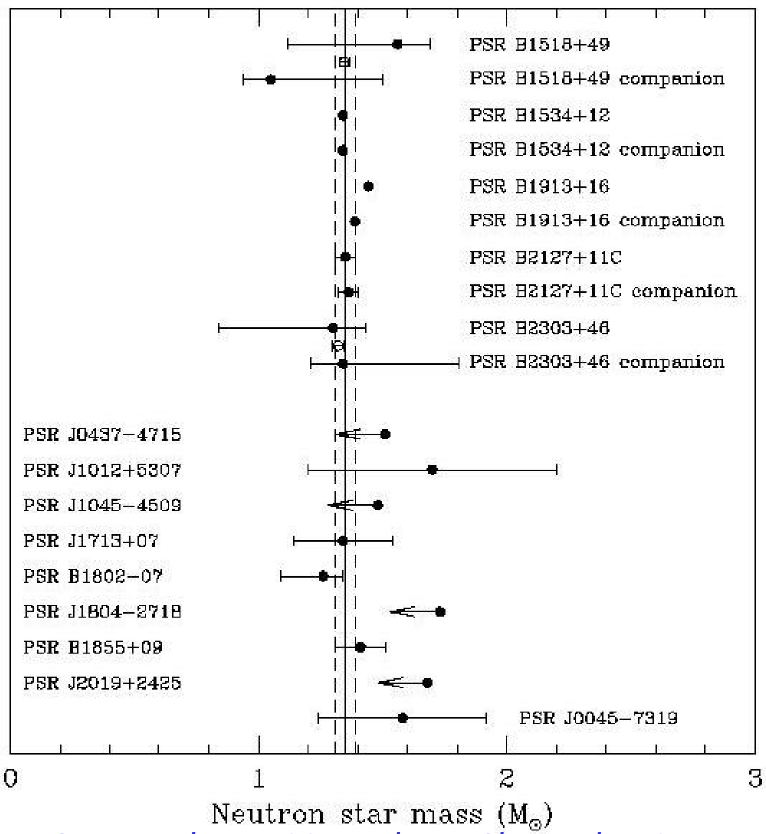
(Crab Pulsar)

http://www.noao.edu/image_gallery/html/im0565.html

Crab Pulsar: N.A.Sharp/NOAO/AURA/NSF

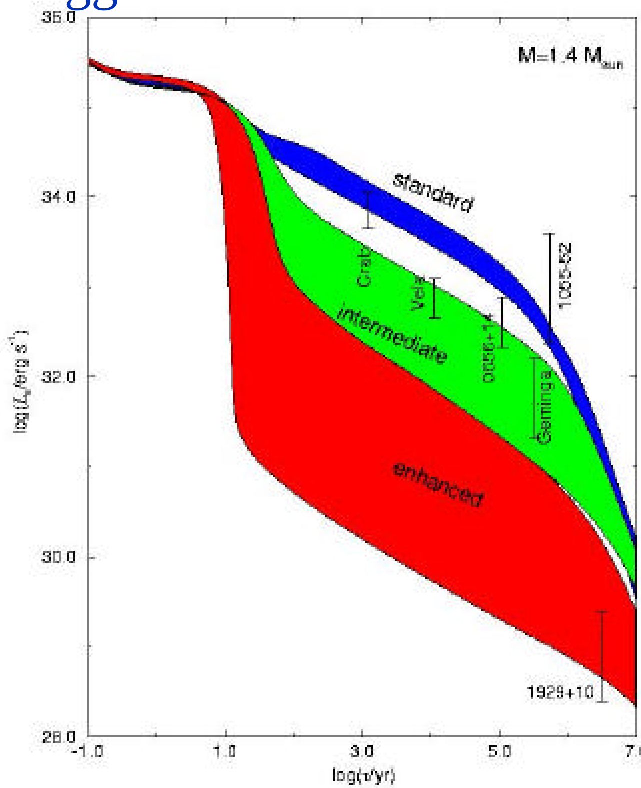
Why Neutron Stars?

Masses ~ 1.4 Solar Masses



S. E. Thorsett and D. Chanrabarty, astro-ph/9803260

- Fastest pulsar spins 642 times per seconds; R < 74 km
- Thermal observations and theory suggest R ~ 5-15 km



www.physik.uni-muenchen.de/sektion/suessmann/astro/cool/

The back of the envelope please…

Don't take this the wrong way…

$$\frac{\text{1.4 Solar Masses}}{\text{10 km Sphere}} = \frac{1.4(1.99 \times 10^{33}\ \text{g})}{4/3\pi(10^{6}\ \text{cm})^{3}}$$

Average density = 6.7×10^{14} g/cm ^{3}

$$\frac{\text{Mass neutron}}{\text{Volume neutron}} = \frac{1.67 \times 10^{-24}\ \text{g}}{4/3\ \pi\ (10^{-13}\ \text{cm})^{3}}$$

= 4.0×10^{14} g/cm ^{3} (billion tons/teaspoon)

… but parts of you are as dense as a neutron star.

$p + e \leftrightarrows n + \nu_e$ (inverse beta and beta decay)

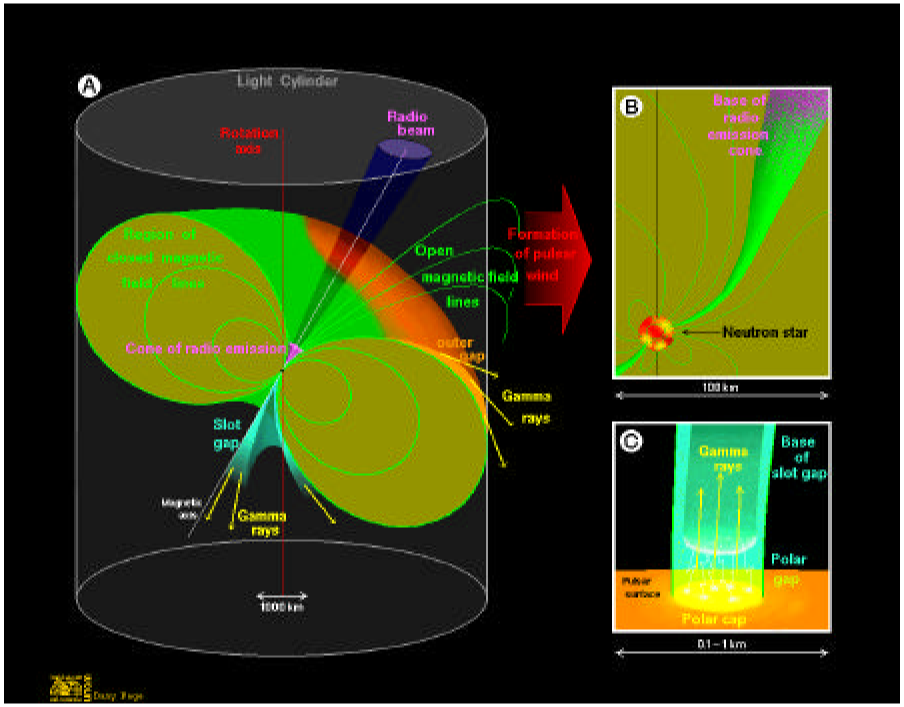
$\mu_p + \mu_e = \mu_n$ (beta equilibrium)

$n_p = n_e$ (charge neutrality)

Seen: SN 1987A!

Nuclear density: 95% n, 5% p & e

More on Pulsars



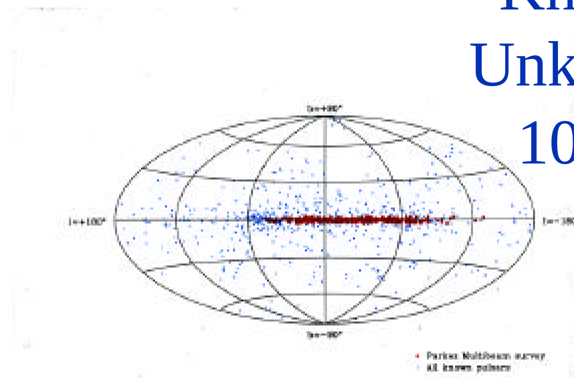
Cosmic lighthouses with terra-gauss magnetic fields !

D. Page

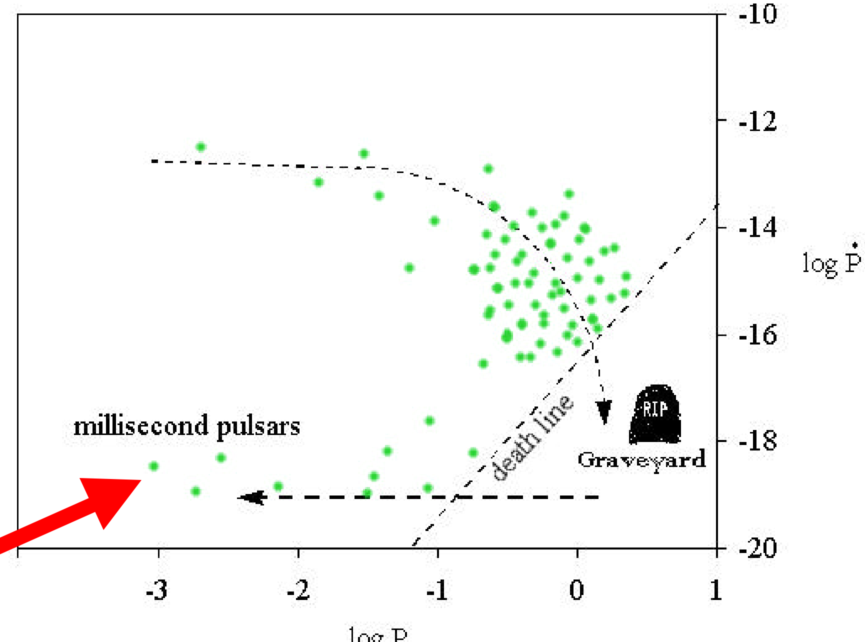
http://www.astroscu.unam.mx/neutrones/home.html

Respun to 642 Hz!
In theory up to 2 kHz.

Known: 1000+
Unknown: up to 100,000 in the Milkyway.

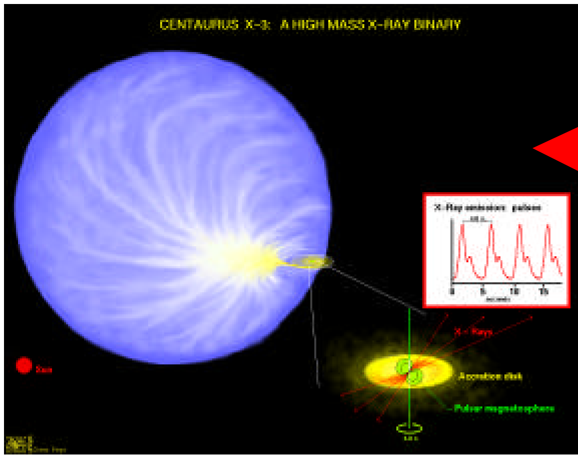


http://online.itp.ucsb.edu/online/neustars00rmode/kaspi/oh/05.html; Vicky Kaspi McGill University, Montreal Canada



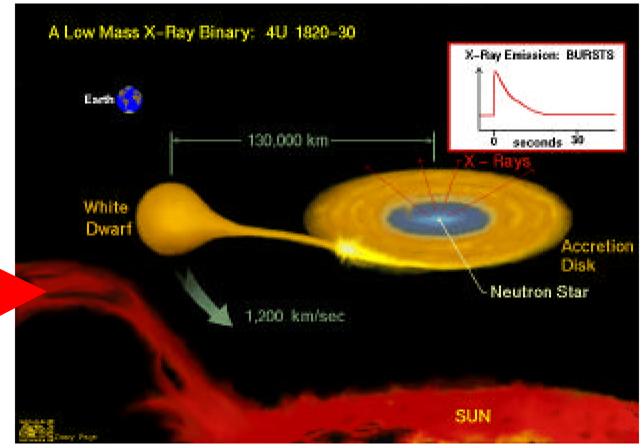
http://astrosun2.astro.cornell.edu/academics/courses/astro201/pulsar_graph.htm

What else is seen?

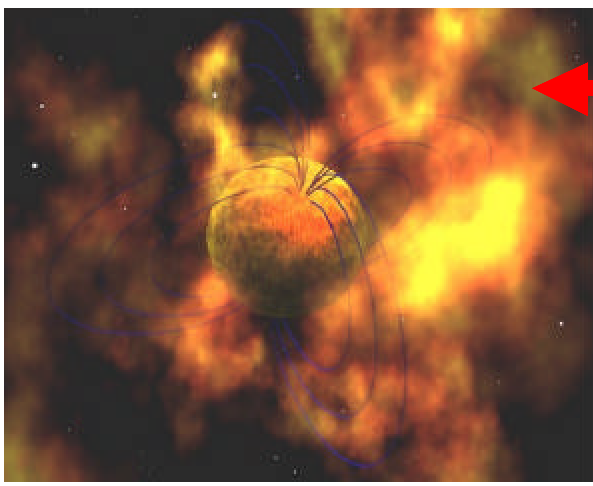


HMXBs

LMXBs



http://www.astroscu.unam.mx/neutrones/home.html

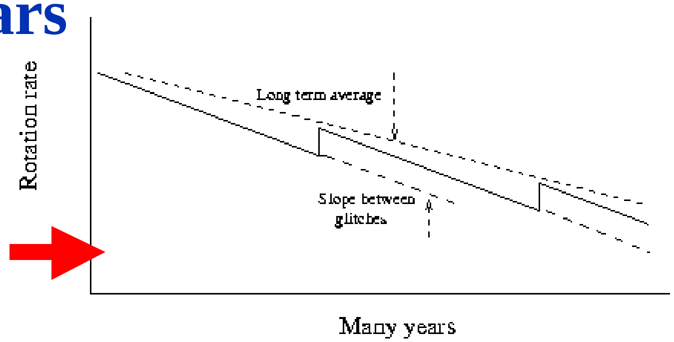


http://antwrp.gsfc.nasa.gov/apod/ap980527.html

Robert Mallozzi (UAH, MSFC)

Magnetars

Pulsar Glitches

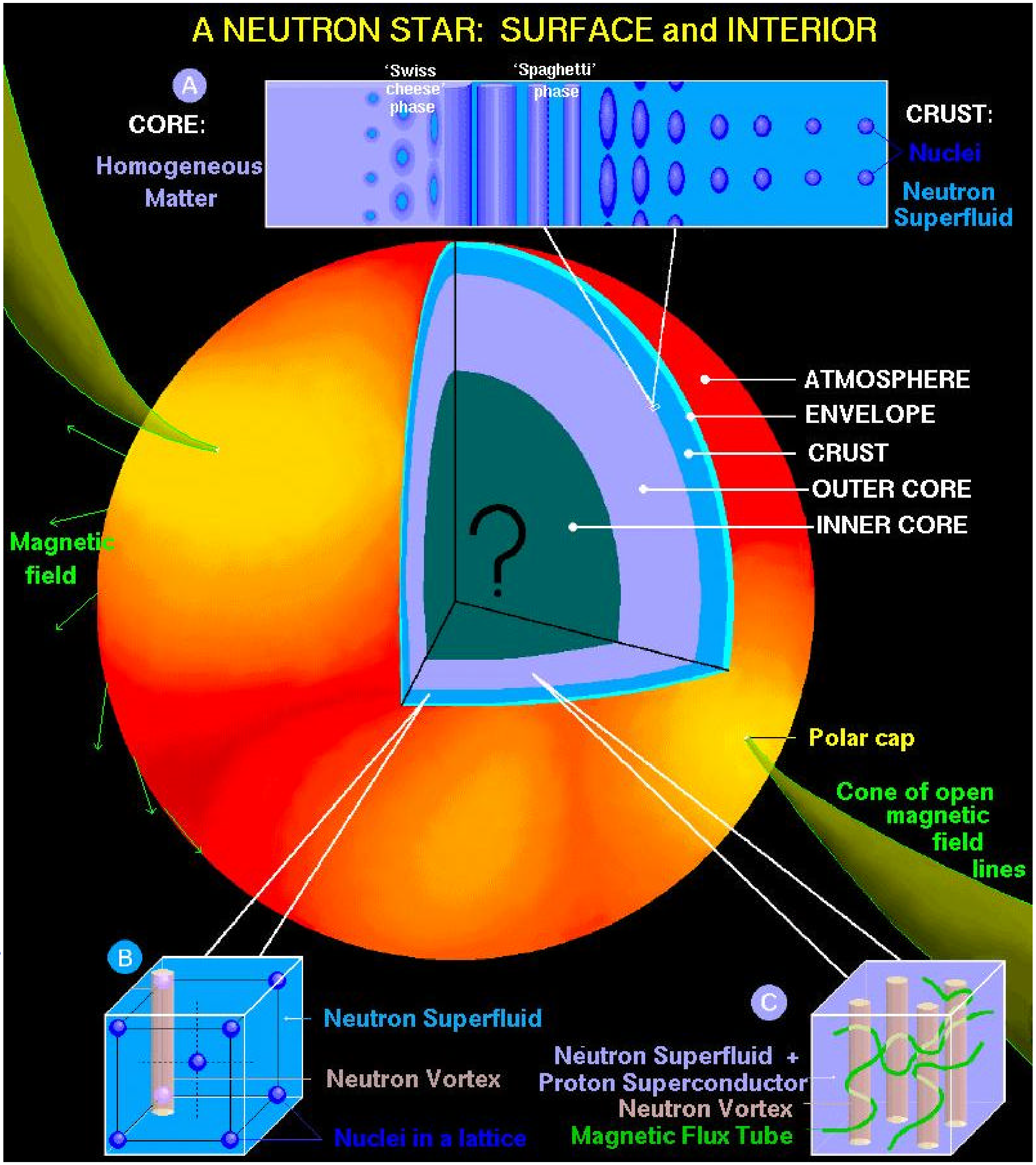


http://www.jb.man.ac.uk/~pulsar/tutorial/tut/tut.html

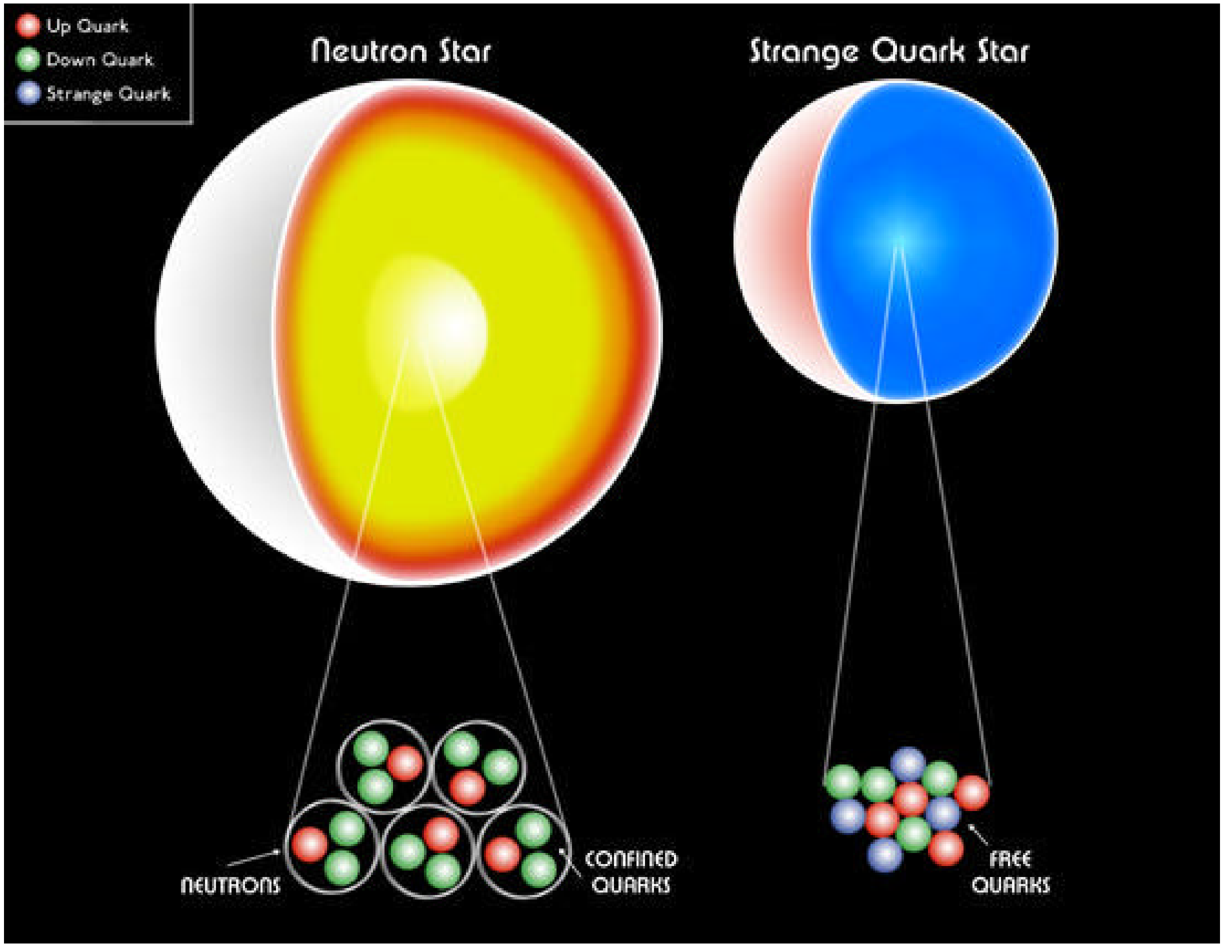
Now it gets interesting…

- Fermi Temp = 10^{12} K
- NS born at 10^{11} K, cools below 10^{9} K within a year; BCS superfluids form.
- Cools to 10^{6} K over 10^{7} K yrs.
- NS are compact “cold” degenerate objects; GR & QM required to understand.

D. Page http://www.astroscu.unam.mx/neutrones/home.html



…and strange…

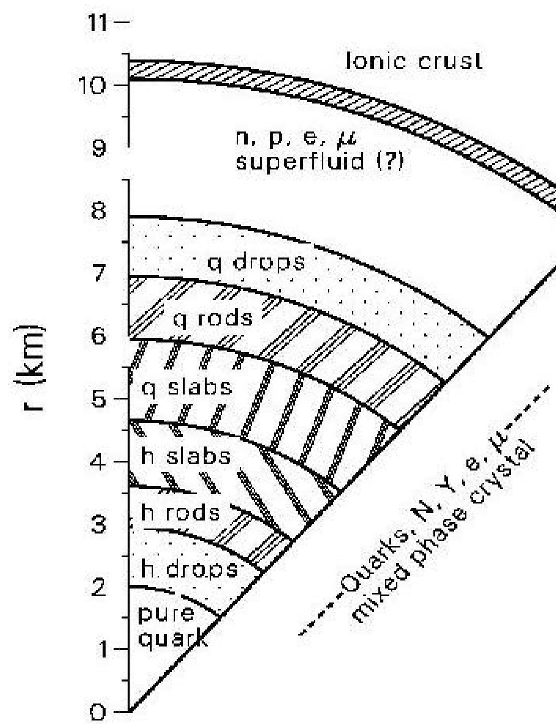


http://chandra.harvard.edu/resources/illustrations/neutronstars_4.html

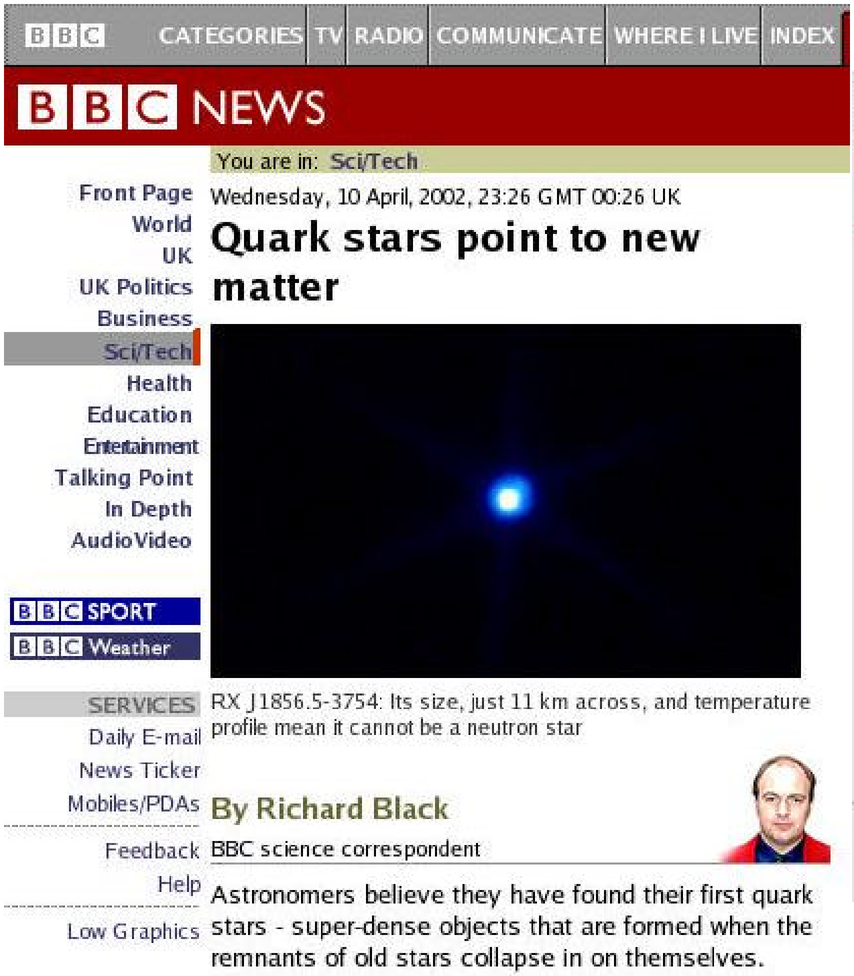
NASA/CXC/SAO

… and hyper-stranger still!

NORMAN K. GLENDENNING
Nuclear Science Division and
Institute for Nuclear and Particle Astrophysics
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720



Strange Stars in the News



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Wednesday, 10 April, 2002, 23:26 GMT 00:26 UK

Quark stars point to new matter

RX J1856.5-3754: Its size, just 11 km across, and temperature profile mean it cannot be a neutron star

By Richard Black
BBC science correspondent

Astronomers believe they have found their first quark stars - super-dense objects that are formed when the remnants of old stars collapse in on themselves.

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Friday, 22 November, 2002, 14:39 GMT

Did quark matter strike Earth?

By Dr David Whitehouse
BBC News Online science editor

A group of researchers have identified two seismic events that they think provide the first evidence of a previously undetected form of matter passing through the Earth.

The so-called strange quark matter is so dense that a piece the size of a human cell would weigh a tonne.

"We can't prove that this was strange quark matter, but that is the only explanation that has been offered so far"

The two events under study both took place in 1993.

Recent Papers

The URL for this search is http://arxiv.org/find/astro-ph/1/ti:+AND+Strange+Star/0/1/0/all/0/1

Showing results 1 through 25 (of 119 total) for ti:(strange AND star)

1. astro-ph/0408217 [abs, ps, pdf, other] :

Title: Electric fields at the quark surface of strange stars in the color-flavor locked phase
Authors: V. V. Usov
Comments: 3 pages, no figures, Phys. Rev. D, in press

2. astro-ph/0407155 [abs, ps, pdf, other] :

Title: Strange Quark Matter and Compact Stars
Authors: Fridolin Weber
Comments: 58 figures, to appear in "Progress in Particle and Nuclear Physics"

3. astro-ph/0406162 [abs, ps, pdf, other] :

Title: Possible evidence of surface vibration of strange stars from stellar observations
Authors: Subharthi Ray, Jishnu Dey, Mira Dey, Siddhartha Bhowmick
Comments: 4 pages, 2 figures, using mn2e.cls. Accepted for publication in MNRAS

4. astro-ph/0403550 [abs, ps, pdf, other] :

Title: Surface gravity of neutron stars and strange stars
Authors: M. Bejger, P. Haensel
Comments: Accepted by A&A

The URL for this search is http://arxiv.org/find/astro-ph/1/ti:+AND+neutron+star/0/1/0/all/0/1

Showing results 1 through 25 (of 300 total) for ti:(neutron AND star)

1. astro-ph/0408467 [abs, ps, pdf, other] :

Title: Type-I superconductivity and neutron star precession
Authors: Armen Sedrakian
Comments: 10 pages, 1 figure

2. astro-ph/0407091 [abs, ps, pdf, other] :

Title: Distinguishing Bare Quark Stars from Neutron Stars
Authors: Prashanth Jaikumar, Charles Gale (McGill U.), Dany Page (UNAM), Madappa Prakash (SUNY Stc
Comments: 8 pages, 5 figures; contribution to proceedings of the 26th annual Montreal-Rochester-Syracuse-T
From Quarks to Cosmology, May 12 - 14 (2004), Concordia University, Montreal, Quebec, Canada

3. astro-ph/0406228 [abs, ps, pdf, other] :

Title: Effect of BCS pairing on entrainment in neutron superfluid current in neutron star crust
Authors: Brandon Carter, Nicolas Chamel, Pawel Haensel
Comments: 30 pages

4. astro-ph/0405262 [abs, ps, pdf, other] :

Title: The Physics of Neutron Stars
Authors: J.M. Lattimer, M. Prakash
Comments: 22 pages, 4 figures and 1 table
Journal-ref: Science Vol. 304 2004 (536-542)

Some Of The Big Questions?

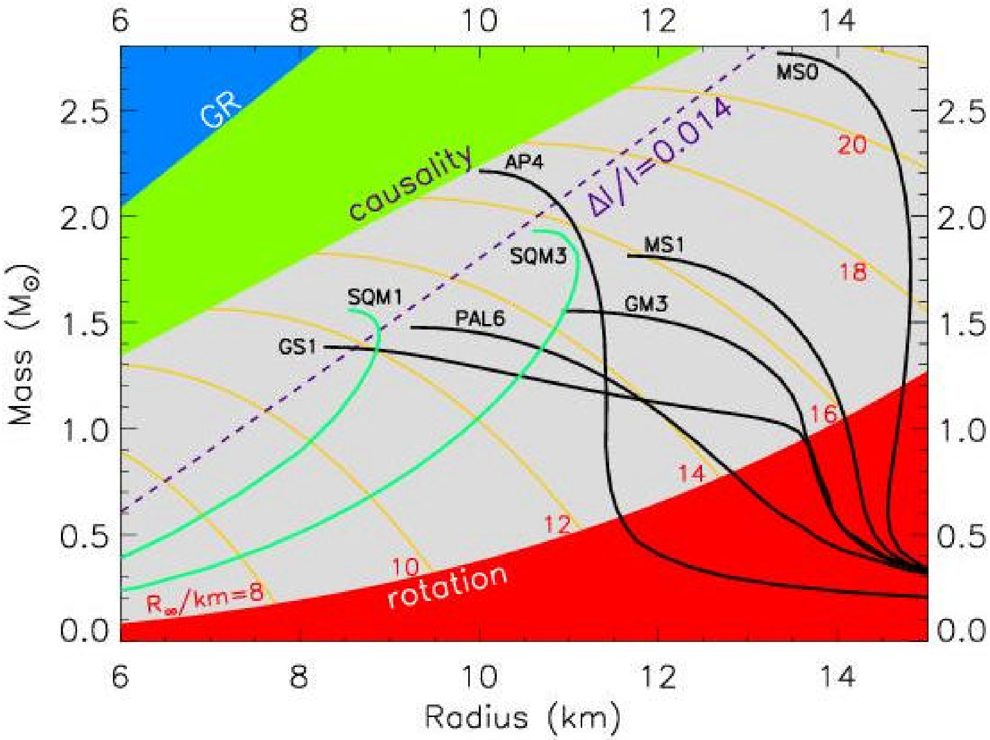


FIG. 2: Mass-radius diagram for neutron stars. Black (green) curves are for normal matter (SQM) equations of state [for definitions of the labels, see [27]]. Regions excluded by general relativity (GR), causality and rotation constraints are indicated. Contours of radiation radii R_∞ are given by the orange curves. The dashed line labeled $\Delta I/I = 0.014$ is a radius limit estimated from Vela pulsar glitches [27].

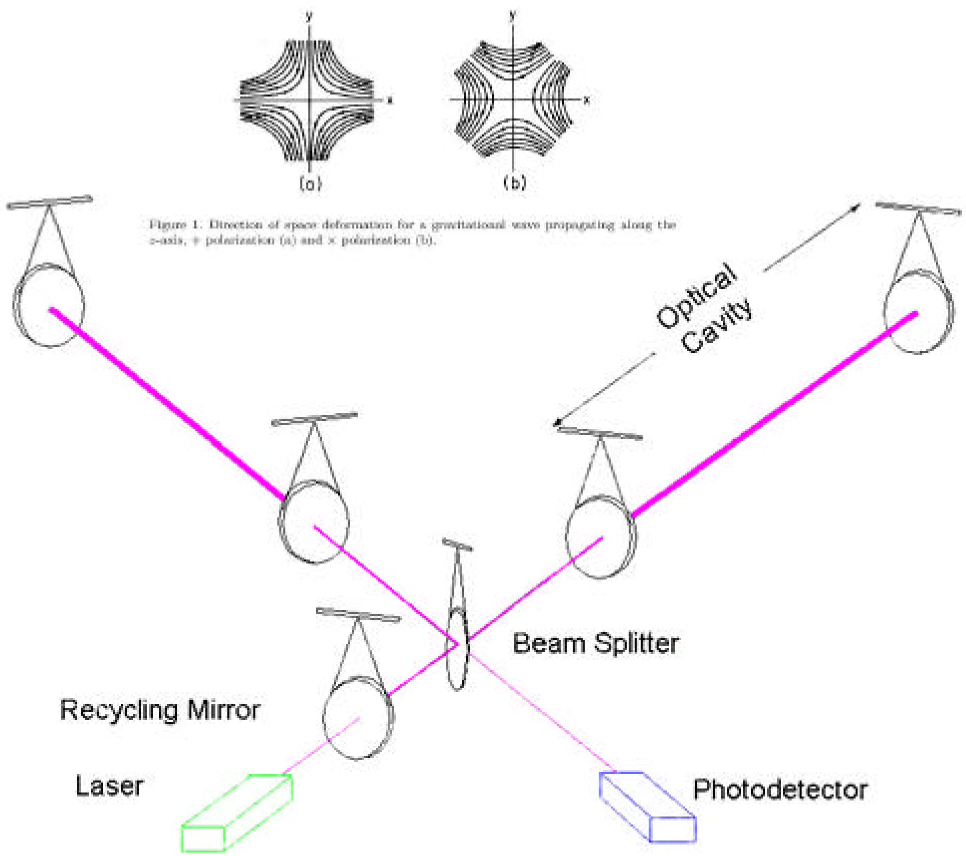
J. M. Lattimer & M. Prakash, astro-ph/0405262

- What is the NS/SQS max. mass; min radius? (1.4-3.5 $M_\odot$? R = ?)
- How fast can NS/SQS spin (up to 2 kHz?) and what controls their spin cycles?
- What are the final states of matter before collapse to BH, i.e., what's inside these stars, really?
- Are quark nuggets hitting the Earth? (Ice-9 Scenerios?)

Laser Interferometer Gravitational-wave Observatories

Gravitational-wave Strain: $h = \Delta L / L$

LIGO is a lab looking for direct detection of GW's.



LIGO is an observatory, "listening" for GW's cosmic spacetime vibrations.

Figures: K. S. Thorne gr-qc/9704042; D. Sigg LIGO-P980007-00-D

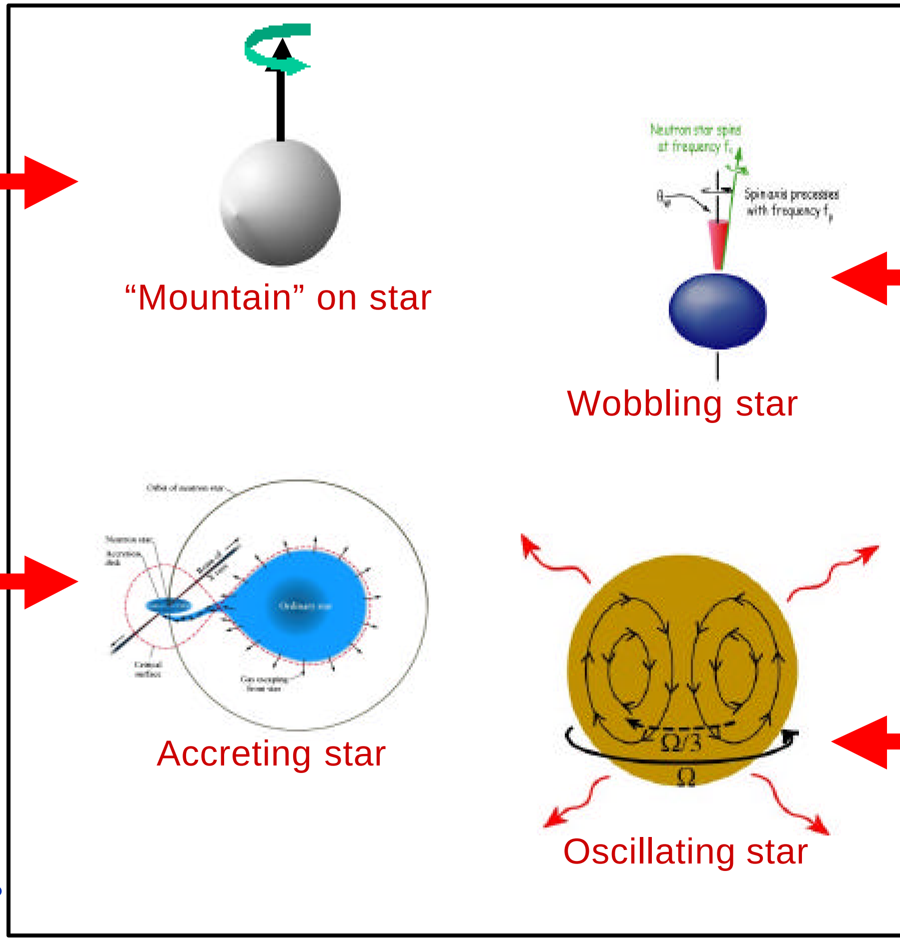
LIGO-G040443-00-W

Continuous Periodic Gravitational-Wave Sources

$$e = \frac{I_1 - I_2}{I}$$

Triaxial Ellipsoid: Ellipticity ε

LMXB: e.g., Sco X-1: balance GW torque with accretion torque.



Free Precession Wobble Angle *q*

Mode with Saturation Amplitude *A*

The back of the envelope please…

Approximate forms of the Quadrupole Formula

$$h = \Delta L / L \approx (G / c^4)(\ddot{Q} / r); \qquad Q \sim MR^2$$

$$\ddot{Q} \sim (MV^2)_{asym.}; \qquad h \sim 10^{-49}\, erg^{-1} (MR^2 f_{GW}^2)_{asym.}$$

- Triaxial ellipsoid: h ~ $(G/c^4)\, \varepsilon MR^2 4 f_{rot}^{\;2}/r \sim 10^{-26}$ (for ellipticity $\varepsilon \sim 10^{-6}$, f_{rot} = 200 Hz, M = 1.4 $M_{\odot}$, R = 10^6 cm, r = 1 kpc = 3×10^{21} cm)
- Precession: h ~ (G/c^4) sin $(2\theta)\, \varepsilon\, MR^2 f_{rot}^{\;2}/r \sim 10^{-27}$ (for ellipticity $\varepsilon \sim 10^{-6}$; wobble angle $\theta = \pi/4$, etc…)
- LMXB Sco-X1: h ~ 10^{-26} (balance GW torque with accretion torque)
- R-modes: h ~ $(G/c^4)\, MA^2R^2 (16/9)\, f_{rot}^{\;2}/r \sim 10^{-26}$ (for saturation amplitude A ~ 10^{-3}, etc…)
- Pulsar Glitch h ~ $(G/c^4)\, MA^2R^2 f_{rot}^{\;2}/r \sim 10^{-32}$ (for glitch amplitude A ~ 10^{-6}, etc…)

LSC Period/CW Search Group
Search Techniques

- ~ 30+ members of the LIGO Science Collaboration.
- Has developed Coherent & Incoherent Search Methods
- Known, Targeted,and All Sky Searches are underway.

$$h_{\text{int}}^2 = 2\int_0^{T_{coh}} |h(t)|^2\, dt$$

$$SNR = h_{\text{int}} / \sqrt{S_n} \sim \sqrt{T_{obs}}$$

$$\langle h_c \rangle_{coh} = 3\times 10^{-26} \frac{\sqrt{S_n}}{10^{-23}\, Hz^{-1/2}} \sqrt{\frac{10^7 s}{T_{obs}}}$$

$$\langle h_c \rangle_{incoh} = 2\times 10^{-25} \frac{\sqrt{S_n}}{10^{-23}\, Hz^{-1/2}} \left(\frac{1800 s}{T_{coh}} \frac{10^7 s}{T_{obs}} \right)^{1/4}$$

Sensitivity Curves

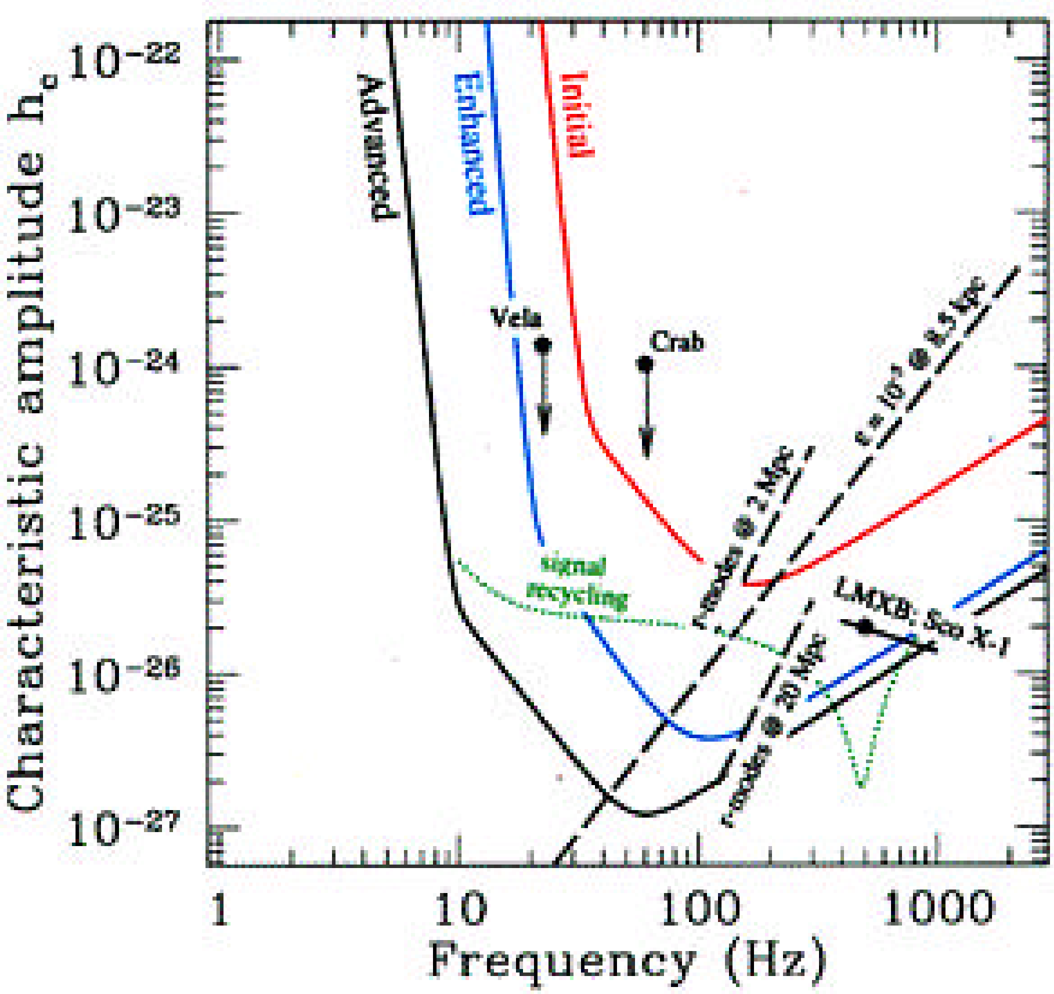
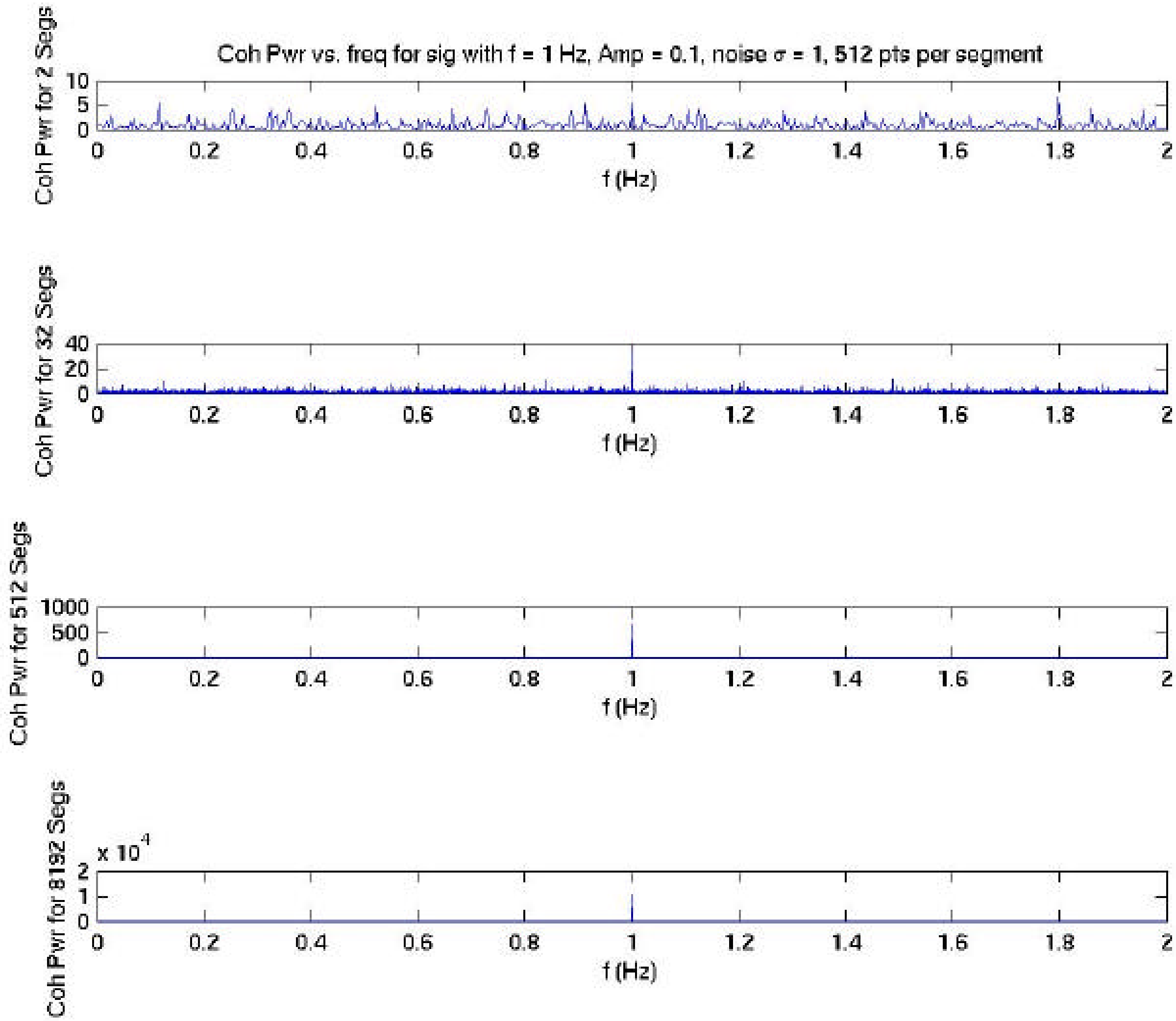


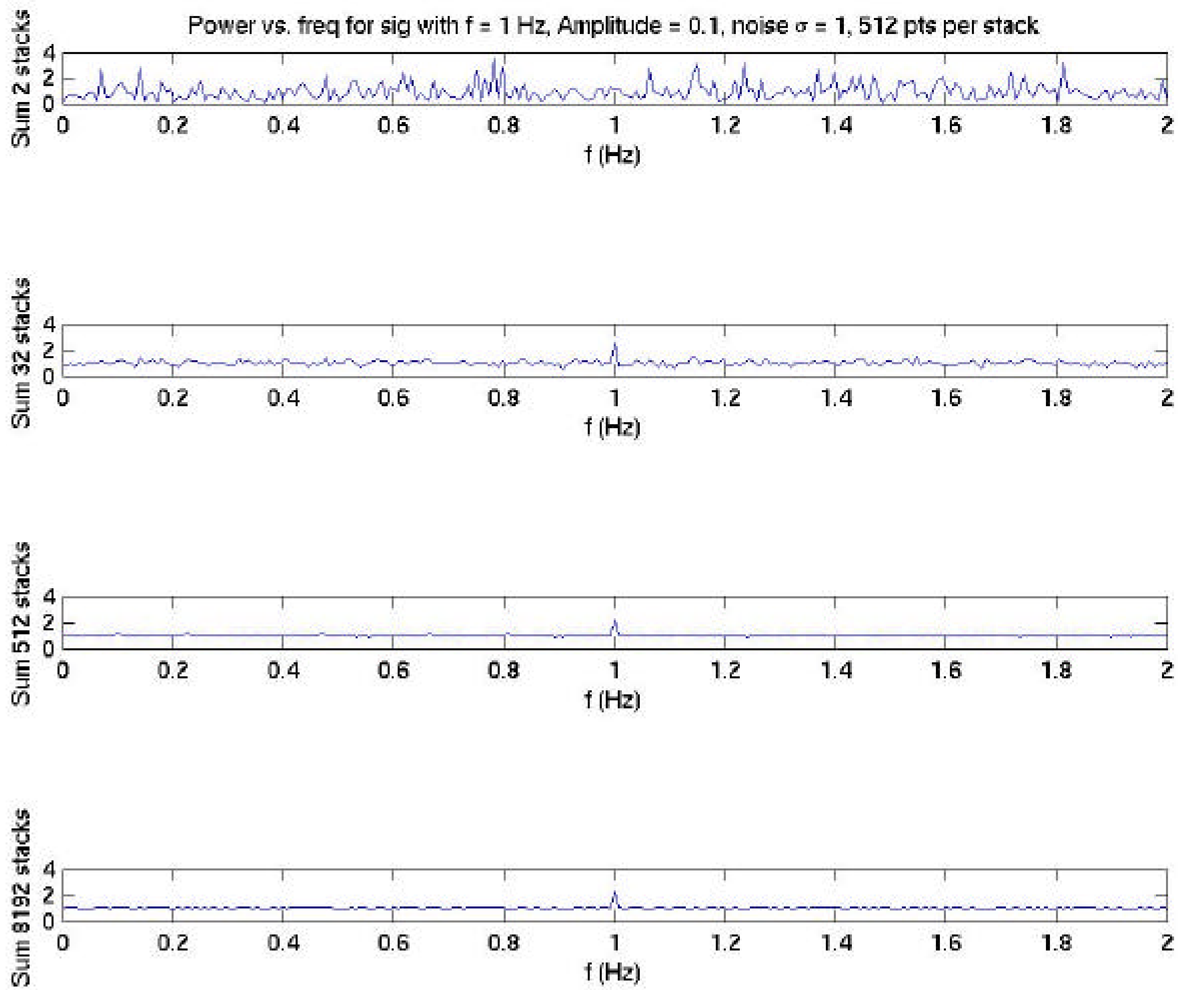
Figure: P. Brady ITP seminar summer 2000

The r-mode saturation amplitude was thought to be much larger in 2000

Coherent Power vs. T_{obs}

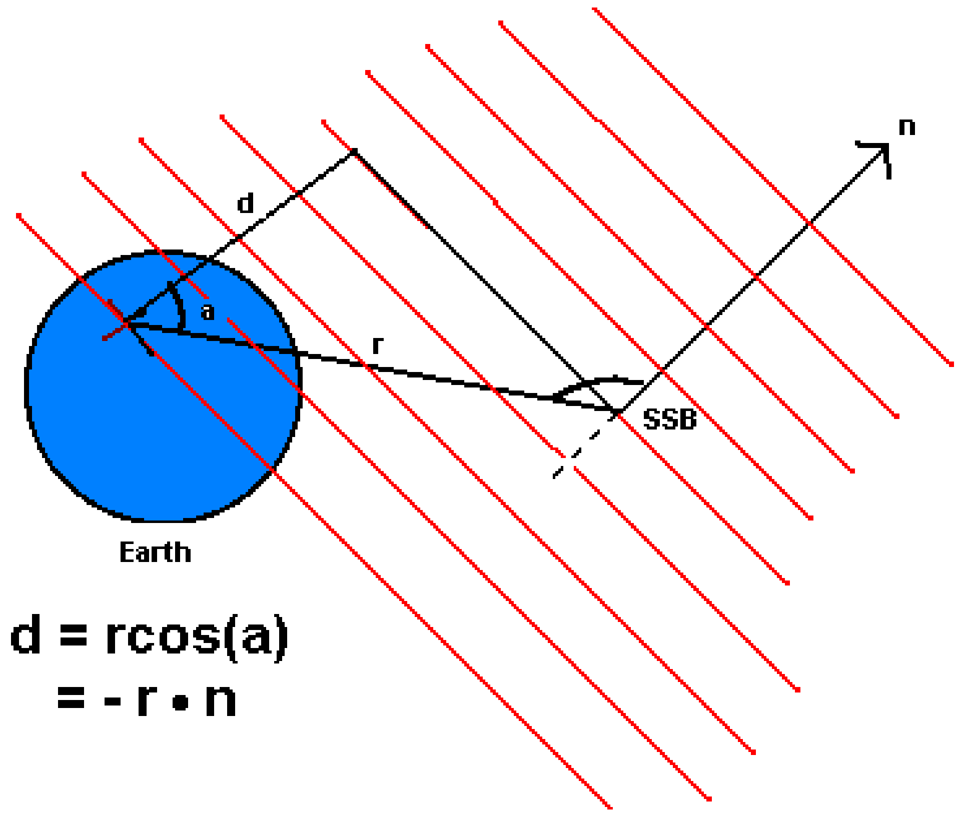


Incoherent Power vs. T_{obs}



Phase Modulation

$$\Phi = \Phi_0 + \sum_{s=0} \frac{f^s}{(s+1)!} \left(t + \frac{\vec{r}(t)}{c} \cdot \hat{n}\right)^{s+1}$$



Frequency Modulation

$$f(t) = \left(1 + \frac{\vec{v}(t)}{c} \cdot \hat{n}\right)\left[f_0 + \sum_{s=1} \frac{f^s}{s!} \left(t + \frac{\vec{r}(t)}{c} \cdot \hat{n}\right)^s \right]$$

- The frequency is modulated by the intrinsic frequency evolution of the source and by the doppler shifts due to the Earth's motion
- The Doppler shifts are important for observation times

$$T \geq 5.5 \times 10^3 \sqrt{\frac{300Hz}{f_0}} \sec.$$

Schutz & Papa gr-qc/9905018; Williams and Schutz gr-qc/9912029; Berukoff and Papa LAL Documentation

Amplitude Modulation

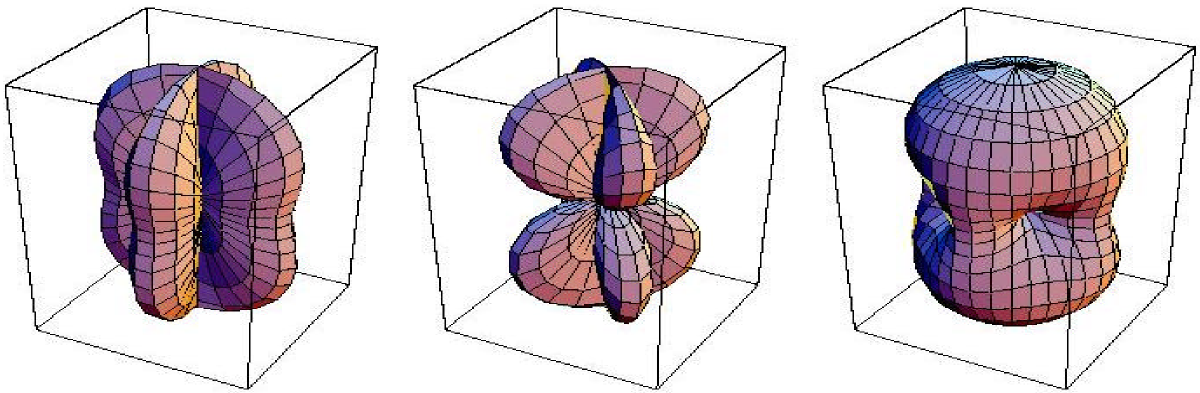


Figure 9. Antenna response function for an interferometric gravitational wave detector. The interferometer is placed at the center of the surrounding box with Michelson arms oriented along the horizontal axes. The distance from a point of the plot surface to the center of the box is a measure for the gravitational wave sensitivity in this direction. The plot to the left is for + polarization, the middle one for × polarization and the right one for unpolarized waves.

Figure: D. Sigg LIGO-P980007-00-D

$$h(t) = \hat{x}\cdot(Mh^{TT}M^{t})\cdot\hat{x} - \hat{y}\cdot(Mh^{TT}M^{t})\cdot\hat{y} = h_{+}(t)F_{+}(t;y) + h_{\times}(t)F_{\times}(t;y)$$

$$h(t) = h_{+}[0.5(1+\cos^{2}q)\cos 2j \cos 2y - \cos q \sin 2j \sin 2y]$$

$$+ h_{\times}[0.5(1+\cos^{2}q)\cos 2j \sin 2y - \cos q \sin 2j \cos 2y]$$

Maximum Likelihood

Likelihood of getting data x for model h for Gaussian Noise:

$$P(x\,|\,h) = \frac{1}{\sqrt{2p}\,s_1} e^{\frac{-(x_1-h_1)^2}{2s_1^2}} \frac{1}{\sqrt{2p}\,s_2} e^{\frac{-(x_2-h_2)^2}{2s_2^2}} \frac{1}{\sqrt{2p}\,s_3} e^{\frac{-(x_3-h_3)^2}{2s_3^2}} \ldots$$

$$c^2 = \sum_j \frac{(x_j - h_j)^2}{s_j^2} = -2\left(\sum_j \frac{x_j h_j}{s_j^2} - \frac{1}{2} \sum_j \frac{h_j h_j}{s_j^2} \right)$$

Chi-squared

$$h_j = f(h_0, \cos i, \Phi_0, y)$$

$$\frac{\partial c^2}{\partial h_0} = 0, \qquad \frac{\partial c^2}{\partial \cos i} = 0, \qquad \frac{\partial c^2}{\partial \Phi_0} = 0, \qquad \frac{\partial c^2}{\partial y} = 0$$

Minimize Chi-squared = Maximize the Likelihood

Coherent Match Filtering

$$X_b = \sum_{a=0}^{M-1}\sum_{j=0}^{N-1} x_{aj} F_{+a}(0) e^{-i\Phi_{ajb}} \qquad x_{aj} = \frac{1}{N}\sum_{k=0}^{N-1} X_{ak}^{SFT} e^{2pijk/N}$$

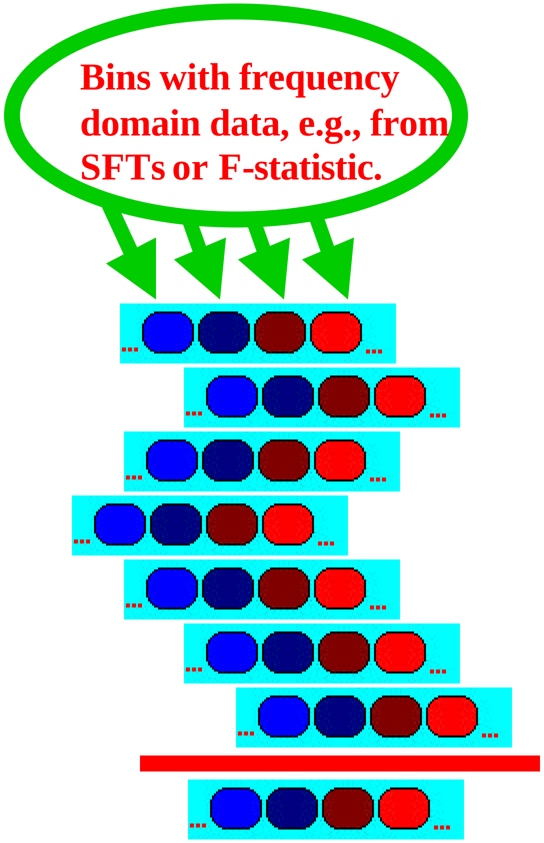
$$\bar{X}_{+b} \cong \sum_{a=0}^{M-1} F_{+a}(0) e^{-if_0} \sum_k \frac{X_{ak}^{SFT}}{\sqrt{S_{ak}}} \frac{\sin 2pk_b - i(1-\cos 2pk_b)}{2p(k-k_b)}$$

$$F = \frac{4}{M} \frac{\langle F_\times^2 \rangle |\bar{X}_+|^2 + \langle F_+^2 \rangle |\bar{X}_\times|^2 - 2\langle F_+ F_\times \rangle \Re e\left(\bar{X}_+ \bar{X}_\times^*\right)}{\langle F_+^2 \rangle \langle F_\times^2 \rangle - \langle F_+ F_\times \rangle^2}$$

Jaranowski, Krolak, & Schutz gr-qc/9804014; Schutz & Papa gr-qc/9905018; Williams and Schutz gr-qc/9912029; Berukoff and Papa LAL Documentation

The StackSlide Search

- An incoherent search method that stacks and slides power to search for periodic sources. *(P. Brady & T. Creighton Phys. Rev. D61 (2000) 082001; gr-qc/9812014.)*
- The periodic search is computationally bound. A hierarchical approach that combines coherent & incoherent methods is needed to optimize sensitivity.
- Sources like LXMBs with short coherence times (~ 2 weeks) require incoherent methods.
- Mendell and Landry are developing the StackSlide Search for the CW group. (The group also uses Hough Transforms and Power Flux, for incoherent searches.)

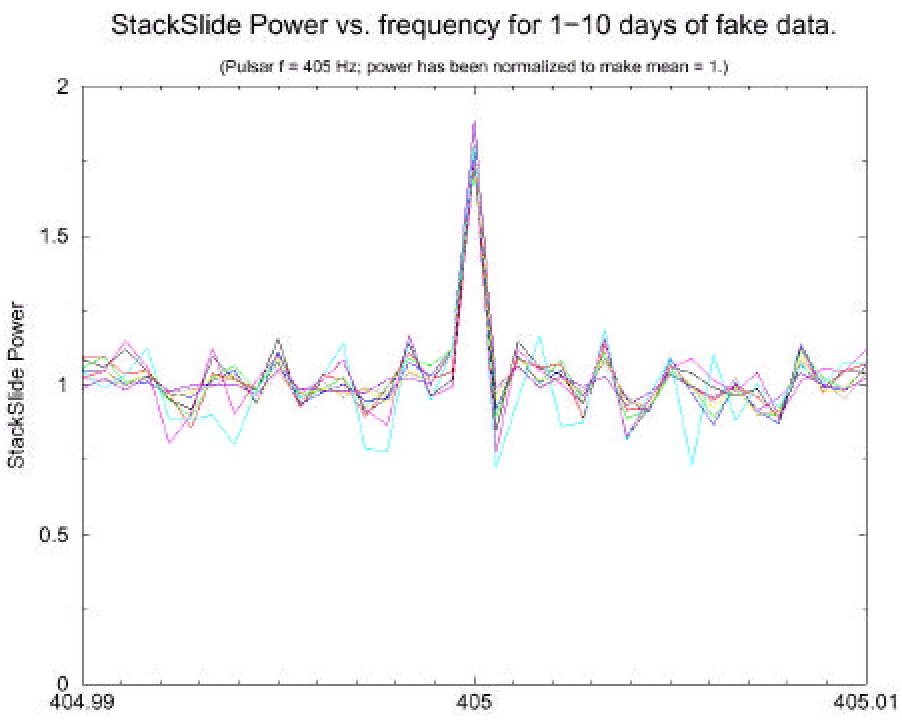


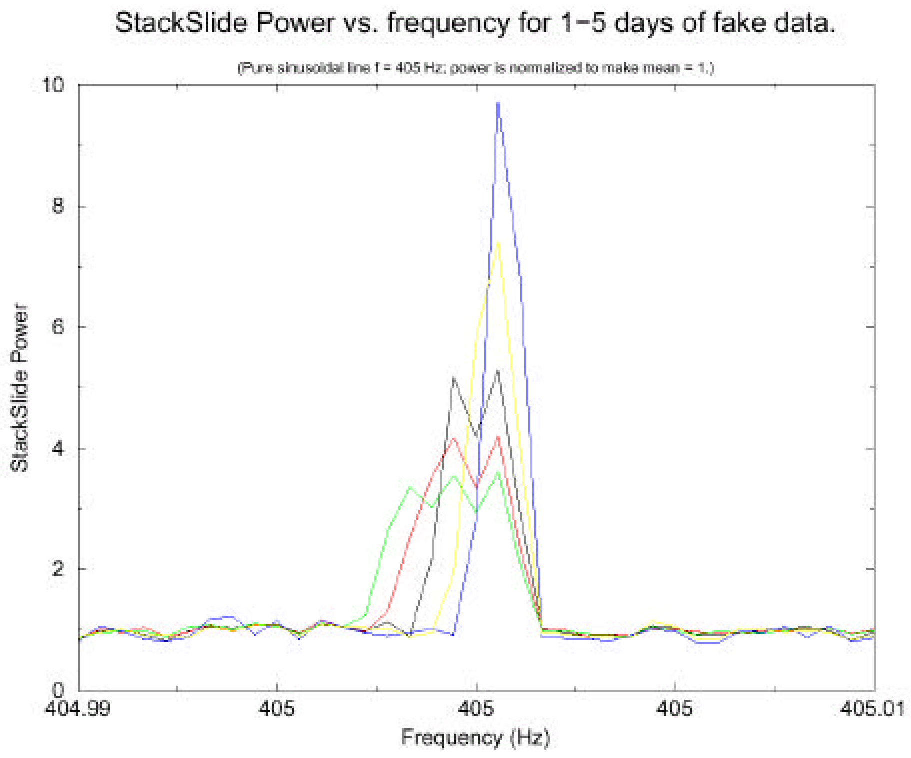
A. **Stack the power.**

B. **Slide to correct for spindown/doppler shifts.**

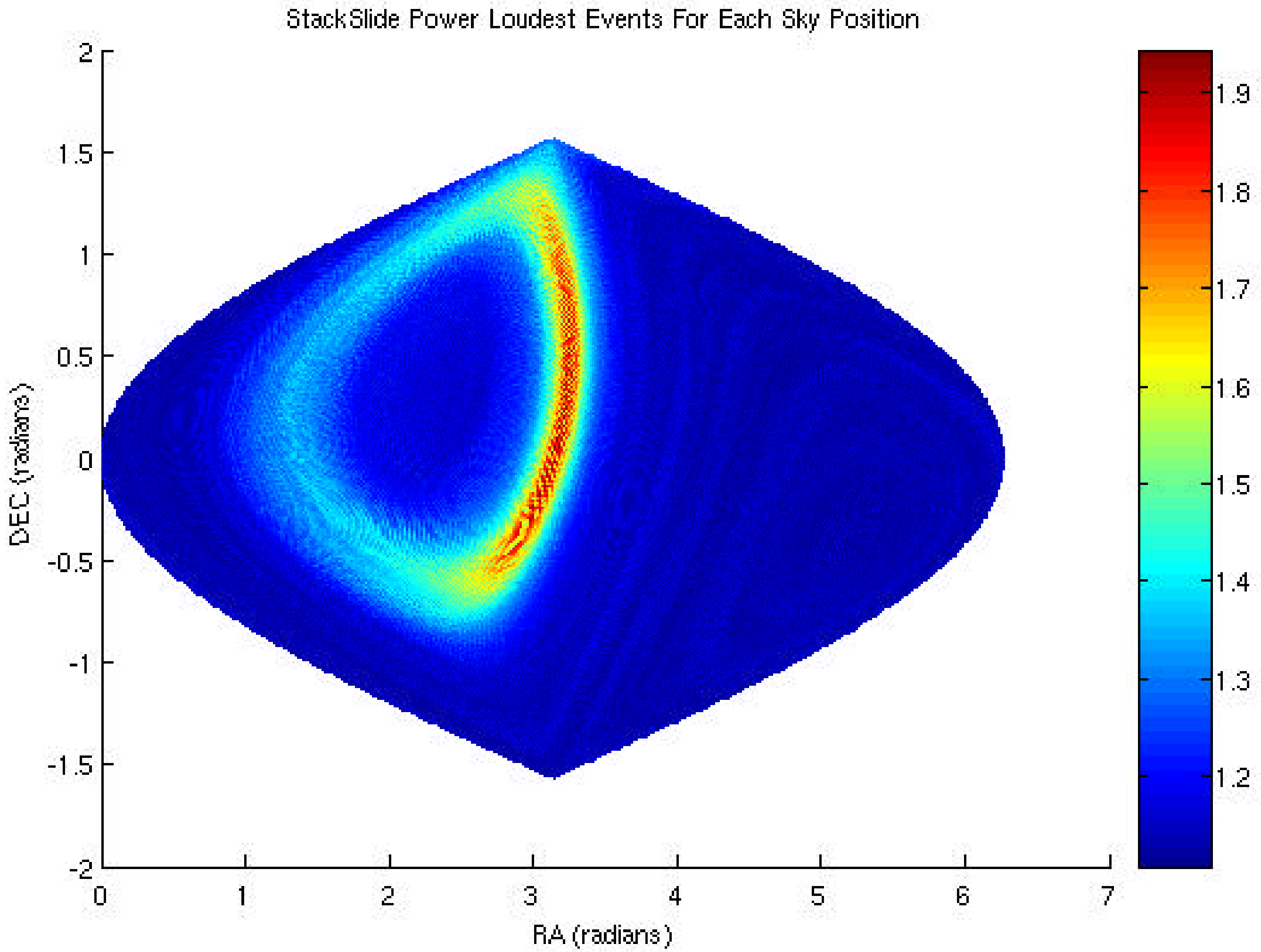
C. **Sum and search for significant peaks.**

Validation: Fake Pulsar vs Fake Instrument Line

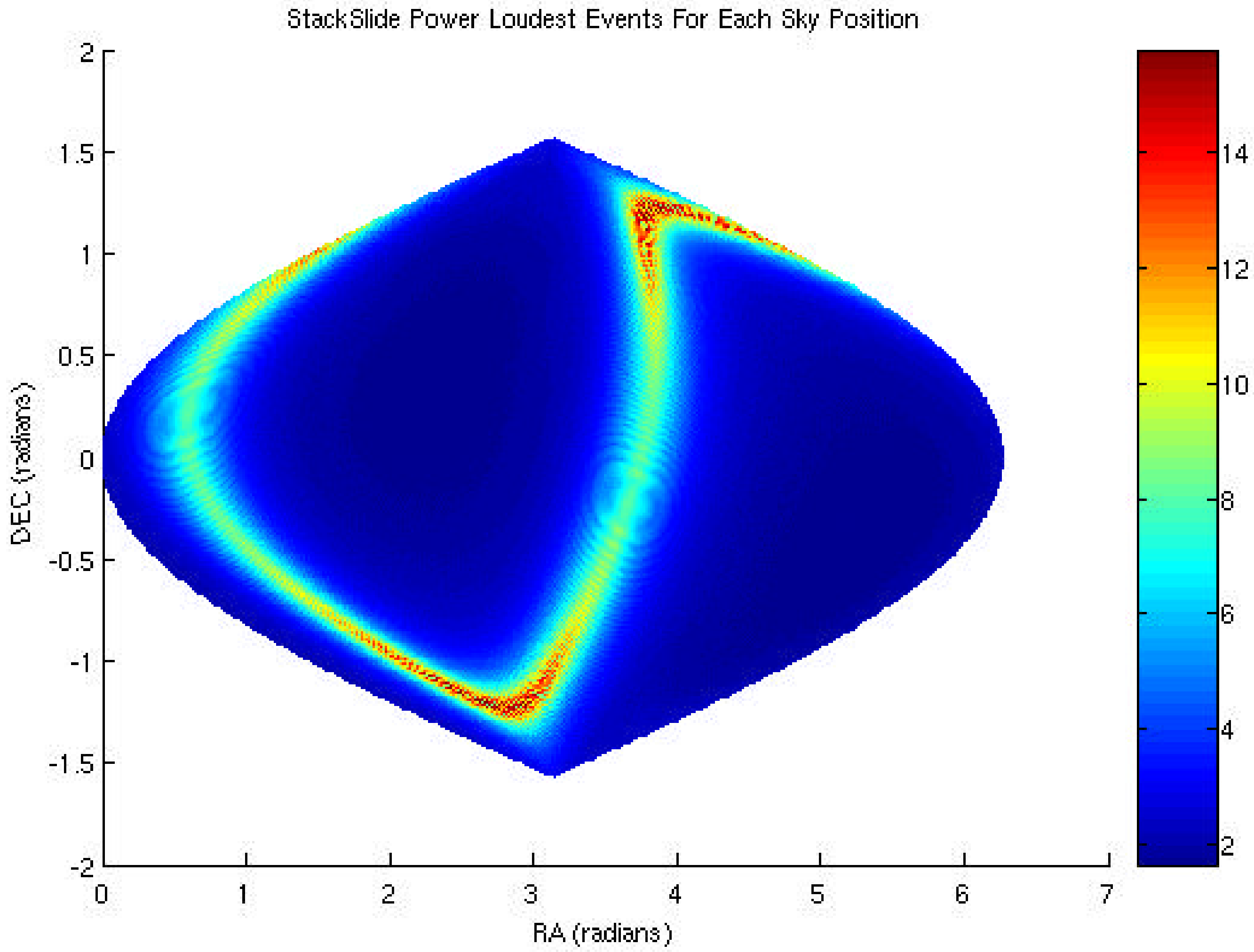




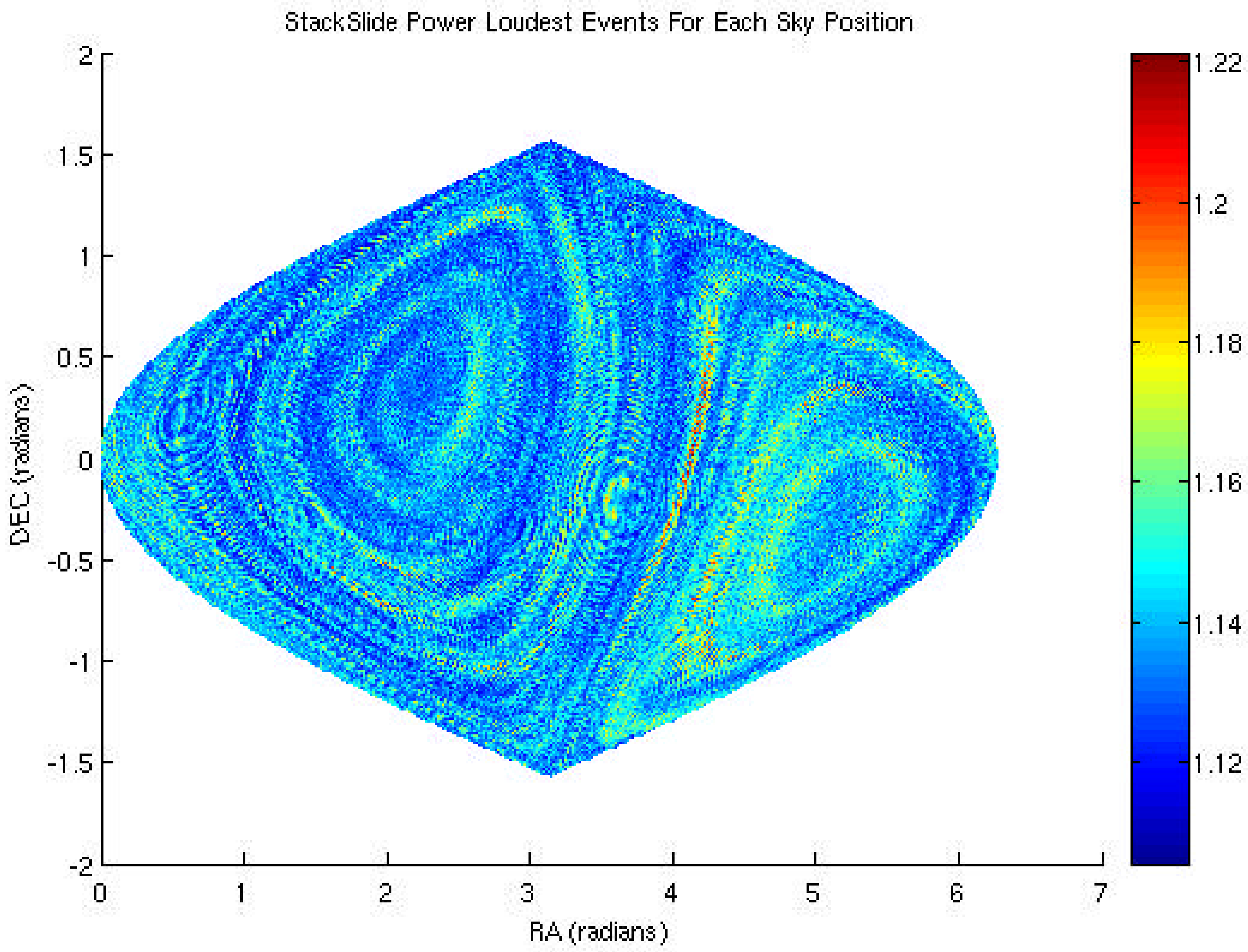
Sky Distribution of Power
Fake Pulsar and Fake Noise:

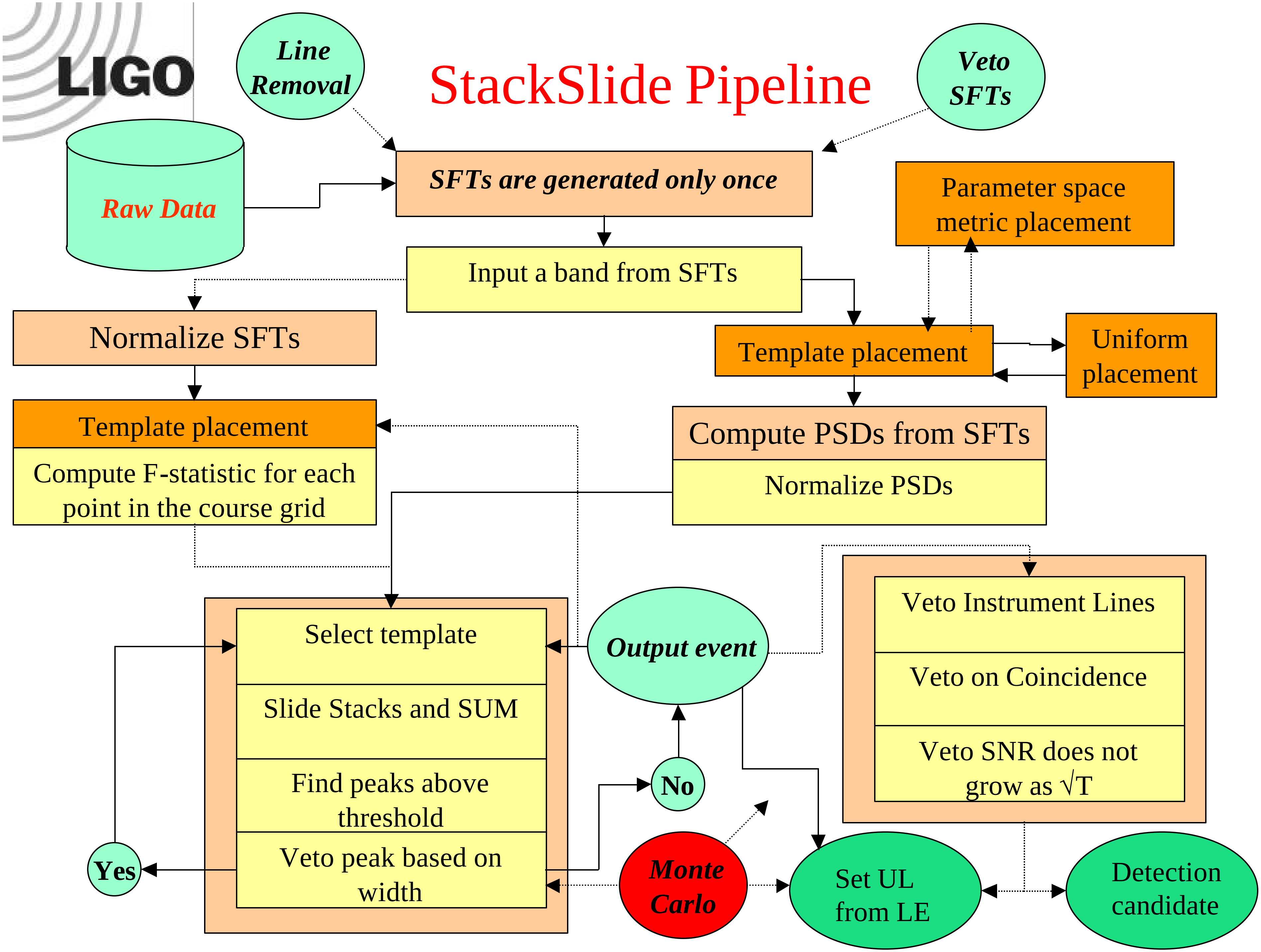


Sky Distribution of Power
Fake Instrument Line and Noise



Sky Distribution of Power
Fake Noise Only:





StackSlide Pipeline
Line Removal
Veto SFTs
Raw Data
SFTs are generated only once
Parameter space metric placement
Input a band from SFTs
Normalize SFTs
Template placement
Uniform placement
Template placement
Compute F-statistic for each point in the course grid
Compute PSDs from SFTs
Normalize PSDs
Select template
Slide Stacks and SUM
Find peaks above threshold
Veto peak based on width
Output event
Veto Instrument Lines
Veto on Coincidence
Veto SNR does not grow as √T
Yes
No
Monte Carlo
Set UL from LE
Detection candidate

Statistics

Gaussian Noise

Rayleigh Dist.

c² variable, with 2 degrees freedom

c² Distribution

$$\tilde{n} = NormalizedFFT(n)$$

$$\tilde{n} = x + iy \qquad |n|^2 = x^2 + y^2$$

$$P(x,y)dxdy = \frac{1}{\sqrt{2p}} e^{-x^2/2} \frac{1}{\sqrt{2p}} e^{-y^2/2} dxdy$$

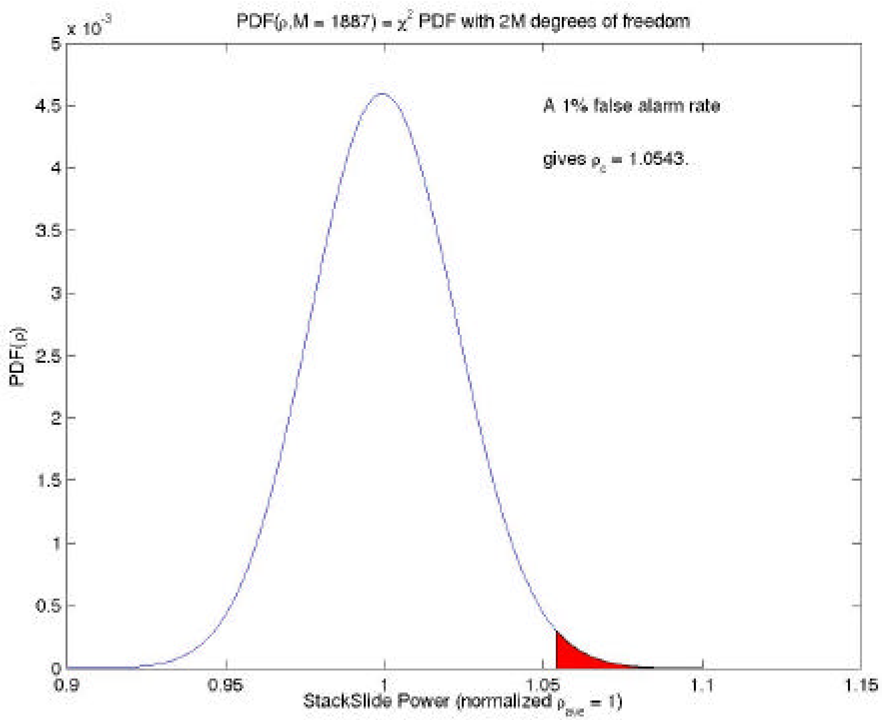
$$x = r\cos f \qquad y = r\sin f$$

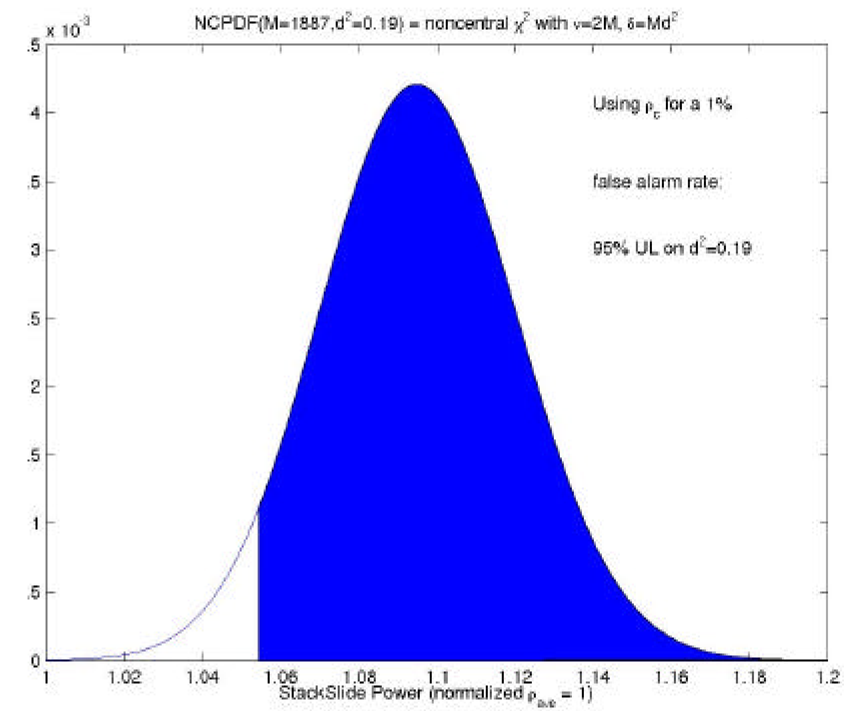
$$P(r)dr = e^{-r^2/2} rdr$$

$$z = r^2 = x^2 + y^2 \qquad \frac{1}{2}dz = rdr$$

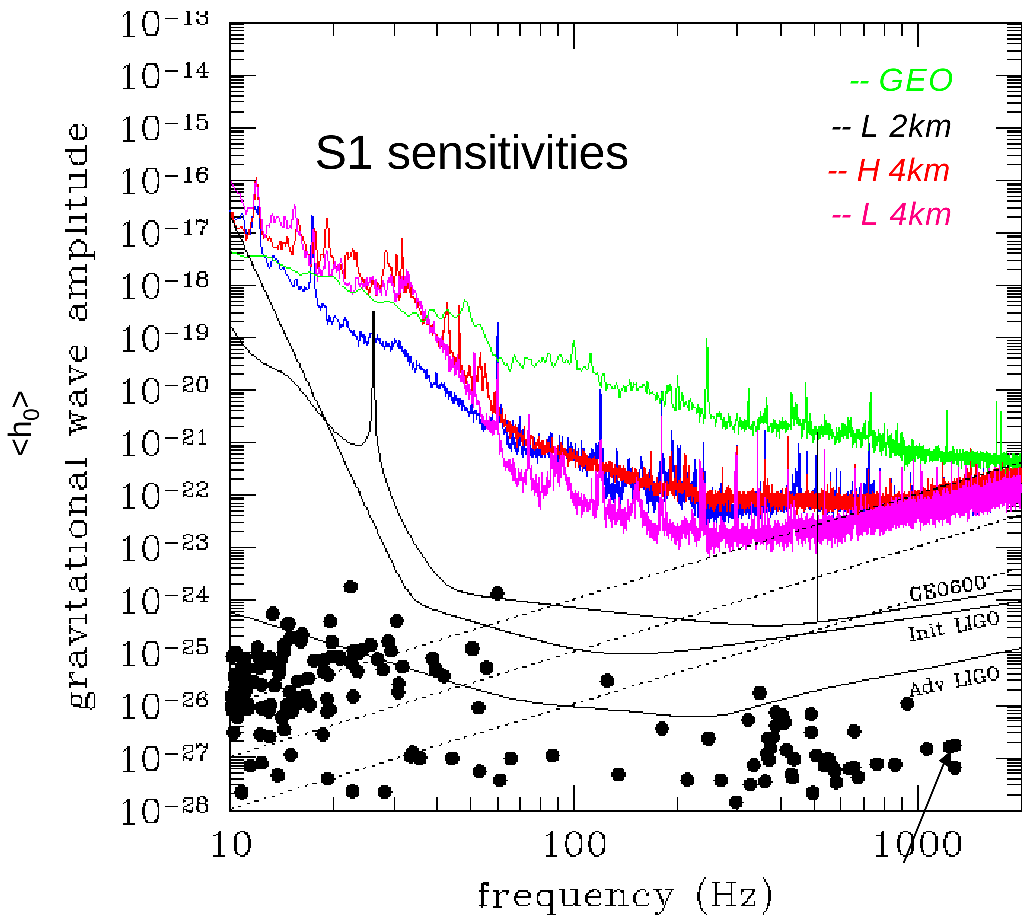
$$P(z)dz = \frac{1}{2} e^{-z/2} dz$$

Statistics: False Alarm Rate; False Dismissal Rate and UL from LE





Result: S1 Coherent Search



$$\langle h_0 \rangle = 11.4 \sqrt{S_h(f) / T_{obs}}$$

PSR J1939+2134
P = 0.00155781 s
f_{GW} = *1283.86 Hz*
dP/dt = -1.0511 10^{-19} s/s
D = 3.6 kpc

- $h_o < 1.4 \times 10^{-22}$ constrains **ellipticity < 2.7 x 10^{-4}** (M=1.4 M_{sun}, r=10 km, R=3.6 kpc)

B Allen and G Woan on behalf of the LIGO Scientific Collaboration : Amaldi 9 July, 2003.